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Habilitation à Diriger des Recherches

Présentée par :

Monsieur **Francisco Miguel MARQUÉS MORENO**

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Titre :

À la recherche d'un femtomètre

Jury :

Mme **María José G. BORGE**, Professeur, CSIC-Madrid, Espagne (*Rapporteur*)
M **Bertram BLANK**, Directeur de Recherche CNRS, CEN-Bordeaux (*Rapporteur*)
M **Wilton CATFORD**, Professeur, University of Surrey, Grande Bretagne (*Rapporteur*)
M **Ginés MARTÍNEZ**, Directeur de Recherche CNRS, SUBATECH-Nantes
M **Nigel ORR**, Directeur de Recherche CNRS, LPC-Caen (*Directeur*)

Liste de Documents

1) HDR en Anglais:

2) CV en Français.

Les articles choisis pour cette HDR sont, dans l'ordre de citation :

– Nuclear Instruments and Methods A365 (1995) 392
– Physical Review Letters 73 (1994) 34
– Physics Letters B 349 (1995) 30
– Physics Letters B 394 (1997) 37
– Physics Reports 284 (1997) 91
– Physics Letters B 381 (1996) 407
– Physical Review Letters 85 (2000) 1404
– Physical Review Letters 87 (2001) 042501
– Nuclear Instruments and Methods A 450 (2000) 109
– Physics Letters B 476 (2000) 219
– Physical Review C 65 (2002) 044006
– arXiv:nucl-ex/0504009
– Physics Letters B 672 (2009) 6
– Physical Review C 64 (2001) 061301
– École Joliot-Curie (2002) 251

A ma famille
Et à tous ceux qui ont participé à cette quête

Francisco Miguel Marqués Moreno

The Quest for a Femtometer

I have tried to summarize in these pages my research during the past 21 years. It started at IFIC-Valencia, then a few years at GANIL and Valencia again, and finally at LPC-Caen since 1994. Though my move to LPC represented a strong thematic change, I have made an effort to find a storyline that follows most of the projects I have participated in, and this storyline is the quest for measuring nuclear distances. Along this path, I will include the cover of the articles I found significant, their full version can be found at the end of this document, in their order of appearance.

1. PHOTON INTERFEROMETRY

I started my research career in 1990, when I finished my studies of Physics at the University of Valencia and joined the IFIC-Valencia Nuclear Physics group of José Lorenzo Ferrero. My first contribution was the study and development of the CPV (charged particle veto) detector for experiments at GANIL with the high-energy photon detector TAPS (two arms photon spectrometer). The design and test of the CPV, in collaboration with the group at KVI-Groningen, was an ideal way to join the research world, as it was simple enough to be undertaken at Valencia, a very small laboratory, but at the same time had a big impact on the whole project, because the high-energy photons TAPS was looking for were very rare, and discriminating them from other more common charged particles was crucial. Indeed, a good title for this HDR could have been "Always looking for rare things"...

I came to GANIL in order to prepare the TAPS campaign of experiments that was going to take place there, and integrated the group of Yves Schutz. The photons we were trying to measure were produced in the collision of heavy ions at several tens of MeV/N, and had energies beyond the Giant Dipole Resonance, between 30 and more than 300 MeV! They were produced by bremsstrahlung in individual *p*-*n* collisions inside the *participant zone*, the overlap between projectile and target. My colleague and friend, Ginés Martínez, was in charge of the study of the dependence of the photon energy with the impact parameter of the collision, and on the production mechanism of the most energetic photons.

My task was to study the interference effects between these photons, when two of them were produced! An even rarer process, the cross-section we measured was $\sigma_{\gamma\gamma} \sim 7\ \mu$b. I focused on the analysis techniques to first automatize the calibration of the multi-detector array (TAPS was made of 320 BaF_2), and then to be sure we were selecting true high-energy $\gamma\gamma$ events. All the algorithms were published in Nuclear Instruments and Methods.

NH ELSEVIER

Nuclear Instruments and Methods in Physics Research A 365 (1995) 392–409

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Identification of photons and particles in the segmented electromagnetic calorimeter TAPS

F.M. Marqués[a,b,1,*], F. Lefèvre[a,2], G. Martínez[b,3], T. Matulewicz[a,4], R.W. Ostendorf[a,5], Y. Schutz[a]

[a] *Grand Accélérateur National d'Ions Lourds, BP 5027, 14021 Caen, France*
[b] *Instituto de Física Corpuscular (CSIC - Universidad de Valencia), 46100 Burjassot, Spain*

Received 19 April 1995

Abstract

The algorithms developed for the identification of one and two hard-photon events detected with TAPS are presented. After a presentation of the energy and time calibrations, the identification of single module events and the shower reconstruction, special emphasis is given to the rejection of the background generated by cosmic rays, π^0 decay and $e^{\pm}$ conversion pairs. The effect of discontinuous showers is also discussed. The method was tested on data taken with TAPS at GANIL for heavy-ion collisions at energies of several tens of A MeV.

Once we selected the $\gamma\gamma$ events, we had to find a way to make the interference effect *appear*, with the added difficulty that the production of neutral pions ($\pi^0 \to \gamma\gamma$) was four times stronger. That was the starting point of my relation with the event-mixing techniques! We finally found a $\gamma\gamma$ interference signal, which was the main objective of the project, well separated from the stronger π^0 one, that we published in Physical Review Letters.

VOLUME 73, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1994

Hard Photon Intensity Interferometry in Heavy Ion Reactions

M. Marqués,* R.W. Ostendorf,† P. Lautridou,‡ F. Lefèvre,§ T. Matulewicz,‖ W. Mittig, P. Roussel-Chomaz, and Y. Schutz
Grand Accélérateur National d'Ions Lourds, BP 5027, 14021 Caen, France

J. Québert
Centre d'Etudes Nucléaires de Bordeaux-Gradignan, 33175 Gradignan, France

J. Díaz, A. Marín, and G. Martínez
Istituto de Física Corpuscular (CSIC - Universidad de Valencia) and Departamento de Física Atómica, Molecular y Nuclear, 46100 Burjassot, Spain

R. Holzmann, S. Hlávač,¶ A. Schubert, R.S. Simon, and V. Wagner**
Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany

H. Löhner, J.H.G. van Pol, R.H. Siemssen, and H.W. Wilschut
Kernfysisch Versneller Instituut, 747 AA Groningen, The Netherlands

M. Franke
II. Physikalisches Institut Universität Giessen, D-35392 Giessen, Germany

Z. Sujkowski
Soltan Institute for Nuclear Studies, 05-400 Swierk, Poland
(Received 16 November 1994)

Intensity correlations between hard photons produced in heavy ion collisions have been measured for $E_\gamma \geq 25$ MeV in the reaction ^{86}Kr + $^{\mathrm{nat}}$Ni at 60A MeV bombarding energy. The observed correlation pattern is interpreted in terms of intensity interference. A correlation length of $C_\sigma = 16 \pm 4$ MeV is found and the deduced photon source extent is discussed.

It was the first observation of this phenomenon with photons of such energies. However, the source size we extracted was $R \sim 12$ fm, much bigger than the expected photon source, the overlap between projectile and target. Ginés Martínez was at that time working with the BUU model on the dependence of photon energy with the density reached during the collision, and found out that, after the initial compression of the overlap zone, the system oscillated and re-compressed a bit later, emitting a second burst of slightly less energetic photons. Since the interferometry pattern is somehow related to the Fourier transform of the emitting source, this double source of photons meant that the correlation function should be modulated by a cosine function, that provided a more coherent interpretation of the data, with a smaller source size of $R \sim 4$ fm, that we published in Physics Letters B.

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Physics Letters B 349 (1995) 30–34
PHYSICS LETTERS B

Density oscillations in systems of colliding heavy ions observed via hard-photon interferometry measurements ⋆

F.M. Marqués [a,b], G. Martínez [b,1], Y. Schutz [a], J. Díaz [b], M. Franke [c], S. Hlaváč [d,2], R. Holzmann [d], P. Lautridou [a,3], F. Lefèvre [a,4], H. Löhner [e], A. Marín [b], T. Matulewicz [a,5], W. Mittig [a], R.W. Ostendorf [a,6], J.H.G. van Pol [e], J. Québert [f], P. Roussel-Chomaz [a], A. Schubert [d,7], R.H. Siemssen [e], R.S. Simon [d], Z. Sujkowski [g], V. Wagner [h], H.W. Wilschut [e], Gy. Wolf [d]

[a] *Grand Accélérateur National d'Ions Lourds, BP 5027, 14021 Caen, France*
[b] *Instituto de Física Corpuscular (CSIC - Universidad de Valencia), 46100 Burjassot, Spain*
[c] *II Physikalisches Institut Universität Gießen, D-35392 Gießen, Germany*
[d] *Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany*
[e] *Kernfysisch Versneller Instituut, 9747 AA Groningen, The Netherlands*
[f] *Centre d'Etudes Nucléaires de Bordeaux-Gradignan, 33175 Gradignan, France*
[g] *Soltan Institute for Nuclear Studies, 05-400 Swierk, Poland*
[h] *Nuclear Physics Institute, 250 68 Řež, Czech Republic*

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Abstract

We have analyzed hard-photon intensity correlations measured in the systems ^{86}Kr+$^{\mathrm{nat}}$Ni at 60.0A MeV and ^{181}Ta+^{197}Au at 39.5A MeV assuming that hard photons are emitted from two distinct sources in space-time. We confirm the existence of the Bose-Einstein correlation between independent hard photons and attribute the origin of the two sources to the density oscillations of nuclear matter generated in intermediate-energy heavy-ion collisions via the incomplete-fusion reaction mechanism.

A more detailed analysis of this double source effect lead us to realize that the double source was not enough to create a significant oscillation in the correlation function. Indeed, by analogy with the two-slit experiments at visible wavelengths or the correlation functions measured in Astronomy for binary stars, we demonstrated that the oscillating pattern in the correlation function was only possible if the double source emitted photons simultaneously. So we had a first photon burst by a single source, the overlap zone with the corresponding source size, $R \sim 3$ fm, followed by the re-compression of the two separate nuclear fragments, that acted like two slits emitting high-energy photons. The interpretation of this analogy was published in Physics Letters B.

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Physics Letters B 394 (1997) 37–42
PHYSICS LETTERS B

Two-slit interference of bremsstrahlung photons from heavy-ion reactions

F.M. Marqués [a,1], G. Martínez [b], T. Matulewicz [b,2], R.W. Ostendorf [b,3], Y. Schutz [b]

[a] *Laboratoire de Physique Corpusculaire, IN2P3-CNRS, ISMRA et Université de Caen, 14050 Caen, France*
[b] *Grand Accélérateur National d'Ions Lourds, BP 5027, 14021 Caen, France*

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Editor: R.H. Siemssen

Abstract

The detailed structure of the hard-photon source created in intermediate-energy heavy-ion reactions is deduced from the analysis of intensity interference measurements. In analogy with the pattern observed in two-slit experiments at visible wavelengths and the correlation function measured for binary stars in astronomy, we find that the data favour the scenario where two nuclear fragments radiate simultaneously during the recompression of the system.

Since photon interferometry at these energies had never been studied, and we had made significant progress in the field, I was told to write a review article for Physics Reports, in which we could review all the details of the theoretical and experimental effort that had been undertaken in those years

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Physics Reports 284 (1997) 91–136
PHYSICS REPORTS

Two-photon correlations: from Young experiments to heavy-ion collision dynamics

F.M. Marqués [1], G. Martínez, T. Matulewicz [2], R.W. Ostendorf [3], Y. Schutz

Grand Accélérateur National d'Ions Lourds, BP 5027, F-14021, Caen, France

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Contents

Abstract

Two-photon correlations are discussed within the formalism of Hanbury–Brown and Twiss interferometry and Bose–Einstein correlations. The technique is presented as a universal tool to study the properties of any boson source – light sources such as stars, or photon and meson sources in the early phase of heavy-ion collisions. The formalism is developed starting from optics and quantum statistics and is finally adapted to the dynamics of heavy-ion collisions. Emphasis is put on the experimental methods derived to display the interference between photons from nuclear reactions. The influence of one-dimensional projections and the detector response on the interpretation of the source properties are discussed. The method is illustrated using experimental data, available only in the intermediate (several tens of A MeV) energy domain. The observed interference signal is interpreted, guided by dynamical phase-space calculations, in terms of source size and reaction dynamics. It is found that photons are emitted as brief light flashes, the relative intensity of which can be linked via model calculations to the incompressibility modulus of nuclear matter. At ultrarelativistic energies, two-photon correlations are presented as a tool to observe the phase transition towards the quark–gluon plasma.

(Note that this is a long paper and only its first page is included in the written document)

2. NEUTRONS FROM THE HALO

The last three years of my research on photon interferometry I was already at LPC-Caen in the Exotic Nuclei group of Nigel Orr. A few days after my arrival the group was running an experiment at GANIL about the one-neutron halo structure of ^{17}B and ^{19}C, so I tried to learn many new things as quick as possible. Hopefully, my experience with the 320 TAPS detectors made the 100 modules of DEMON (détecteur modulaire de neutrons) seem too few! The ^{19}C beam intensity had been much lower than expected, and we got no ^{17}B at all, so I tried to check if the experiment had been successful by setting up the analysis programs and having a look to the reaction channel that was more straightforward to analyze, the core breakup.

During the first steps of the analysis I remember having a hard time not rejecting neutrons, after several years doing so with TAPS! The core+n dissociation channel, in our case ^{18}C+n, was hard to extract because the beam stopped in the charged particle telescope, in which any ^{18}C was overwhelmed by all the ^{19}C beam particles that had gone through the target. On the other hand, the core breakup channel was relatively easy: a fragment with $Z < 6$ plus neutrons. For a neutron halo system, this channel should give two neutron angular contributions, a wide one from the neutrons liberated in the breakup of the core, ^{18}C, plus a narrow one corresponding to the *spectator* halo neutron due to its spatially extended wave function. And this is what we found, a narrow component of about 40 MeV/c FWHM from the halo of ^{19}C, plus a wide one of about 160 MeV/c FWHM from the core, similar to that obtained from other beam particles. This result was the first *narrow neutron* one for ^{19}C (the core one had been already measured at MSU) and was published in Physics Letters B.

ELSEVIER

Physics Letters B 381 (1996) 407–412

PHYSICS LETTERS B

Neutrons from the breakup of ^{19}C

F.M. Marqués [a], E. Liegard [a], N.A. Orr [a,1], J.C. Angélique [a], L. Axelsson [b], G. Bizard [a], W.N. Catford [c], N.M. Clarke [d], G. Costa [e], M. Freer [d], S. Grévy [f], D. Guillemaud-Mueller [f], G.J. Gyapong [c], F. Hanappe [g], P.G. Hansen [h], B. Heusch [e], B. Jonson [b], C. Le Brun [a], F.R. Lecolley [a], F. Lefebvres [a], M. Lewitowicz [i], G. Martínez [i], A.C. Mueller [f], T. Nilsson [b], A. Ninane [j], G. Nyman [b], B. Petersen [k], F. Pougheon [f], K. Riisager [k], M.G. Saint-Laurent [i], Y. Schutz [i], M. Smedberg [b], O. Sorlin [f], L. Stuttgé [e], D.D. Warner [ℓ]

[a] *Laboratoire de Physique Corpusculaire, IN2P3-CNRS, ISMRA et Université de Caen, 14050 Caen Cedex, France*
[b] *Fysiska Institutionen, Chalmers Tekniska Högskola, S-412 96 Göteborg, Sweden*
[c] *Department of Physics, University of Surrey, Guildford, Surrey GU2 5XH, United Kingdom*
[d] *School of Physics and Space Research, University of Birmingham, P.O. Box 363, Birmingham B15 2TT, United Kingdom*
[e] *Centre de Recherche Nucléaire, IN2P3-CNRS, BP 28, 67037 Strasbourg Cedex 2, France*
[f] *Institut de Physique Nucléaire, IN2P3-CNRS, 91406 Orsay Cedex, France*
[g] *Université Libre de Bruxelles, CP 226, B-1050 Bruxelles, Belgium*
[h] *NSCL, Michigan State University, East Lansing, MI 48824-1321, United States*
[i] *GANIL (CEA/DSM – CNRS/IN2P3), BP 5027, 14021 Caen, France*
[j] *Institut de Physique, Université Catholique de Louvain, B-1328 Louvain-la-Neuve, Belgium*
[k] *Institut for Fysik og Astronomi, Aarhus Universitet, DK 8000 Aarhus C, Denmark*
[ℓ] *Daresbury Laboratory, Warrington, Cheshire WA4 4AD, United Kingdom*

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Abstract

Neutrons arising from the breakup of a 30 MeV/nucleon ^{19}C beam on a tantalum target have been measured using the 98 element array DEMON. A narrow, forward peaked neutron angular distribution, with a corresponding momentum spread considerably smaller than those measured simultaneously for ^{21}N, ^{22}O and ^{24}F, was observed for charged fragments with $Z < Z_{\mathrm{proj}}$. Interpreted in terms of the core-breakup reaction model, the results support the existence of a one neutron halo in ^{19}C.

3. PHOTONS FROM THE HALO?

I got my CNRS position at LPC, and after my first years of learning what others had done in the halo field, we began to think about things we could do differently. The first idea came up naturally: since the high-energy photons TAPS had been measuring were produced by bremsstrahlung in individual p-n collisions, and Ginés Martínez had shown that their energy slope depended on the momentum of those nucleons, why not measure the momentum of the halo neutrons through their bremsstrahlung on a proton target? A spatially extended neutron has a narrow momentum distribution and should lead to a softer photon energy spectrum.

Cross-sections being much smaller for bremsstrahlung production (several μb) than breakup (hundreds of mb), this technique would only be applicable to the halo system the closest to stability, ^{6}He (α+n+n structure). I order to isolate the bremsstrahlung from the two halo neutrons, the same measurement was planned at KVI-Groningen with a

^{4}He beam, and the results published in Physical Review Letters.

VOLUME 85, NUMBER 7 PHYSICAL REVIEW LETTERS 14 AUGUST 2000

Coherent Bremsstrahlung in the $\alpha + p$ System at 50 MeV/nucleon

M. Hoefman,[1] L. Aphecetche,[2,*] J. C. S. Bacelar,[1] H. Delagrange,[2,*] P. Descouvemont,[3] J. Díaz,[4] D. d'Enterria,[2,*] M.-J. van Goethem,[1] R. Holzmann,[5] H. Huisman,[1] N. Kalantar-Nayestanaki,[1] A. Kugler,[6] H. Löhner,[1] F. M. Marqués,[7] G. Martínez,[2,*] J. G. Messchendorp,[1] R. W. Ostendorf,[1] S. Schadmand,[1,†] R. H. Siemssen,[1,‡] R. S. Simon,[5] Y. Schutz,[2,*] R. Timmermans,[1] R. Turrisi,[1,§] M. Volkerts,[1] V. Wagner,[6] H. Weller,[8] H. W. Wilschut,[1] and E. Wulf[8]

[1]*Kernfysisch Versneller Instituut, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands*
[2]*Grand Accélérateur National d'Ions Lourds, F-14076 Caen Cedex 5, France*
[3]*Université Libre Bruxelles CP229, B-1050 Brussels, Belgium*
[4]*Instituto de Física Corpuscular, E-46100 Burjassot, Spain*
[5]*Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany*
[6]*Nuclear Physics Institute, 25068 Řež u Prahy, Czech Republic*
[7]*Laboratoire de Physique Corpusculaire, F-14050 Caen Cedex, France*
[8]*TUNL Duke University, Durham, North Carolina 27708-0308*
(Received 28 March 2000)

Photons originating from coherent bremsstrahlung have been measured over a large dynamic range for the reaction of 200 MeV α particles with protons. At low photon energies the bremsstrahlung spectrum exhibits the classical behavior with an approximate $1/E_\gamma$ shape. At higher photon energies there is a pronounced contribution from capture into the unbound ground state and first excited state of ^{5}Li. These results allow one, for the first time, to test theoretical models for a consistent description of bremsstrahlung and radiative capture in a complex system. Calculations predict both features qualitatively but fail to account for their relative importance.

To our surprise, most of the high-energy photons in the α+p system did not came from bremsstrahlung, but from radiative proton capture! Into the two first states of unbound ^{5}Li, generating one photon peak for each of them, on top of the exponential bremsstrahlung spectrum.

We had to reconsider our ^{6}He proposal at GANIL, that had been aimed at measuring small differences in the slope of the photon spectra. Now the photon probe seemed to be even better, because the proton could be captured by the different subsystems of the α+n+n structure as it had been at KVI, and each of these captures (on $n/2n/\alpha/^5$He) would lead to different photon peaks, much easier to observe.

The experiment was a complete challenge. Besides being the first time someone tried to measure this, it was going to be the first time the Château de Cristal (an array of 74 BaF_2) was going to be used for the detection of high-energy photons, since TAPS had already left GANIL, and the first time we were going to use a liquid Hydrogen target! Too many first times. But the PhD student, Emmanuel Sauvan, played a key role to make all these first times run smooth and easily, despite being involved in another program that made the other half of his PhD, the measure of momentum distributions in the -1n channel for several tens of neutron-rich nuclei!

We took the liquid target *risk* because running on a CH_x plastic and then subtracting a Carbon run would not have been appropriate, since bremsstrahlung from Carbon would have overwhelmed the proton capture signal we were looking for. And, despite capture into ^{7}Li being the strongest channel, we did observe quasi-free capture on one halo neutron, the α core, and ^{5}He, through the corresponding photon energy peak in coincidence with the subsystem+proton in the SPEG spectrometer. These results were published in Physical Review Letters.

VOLUME 87, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 2001

Radiative Proton Capture on ^{6}He

E. Sauvan,[1,*] F. M. Marqués,[1,†] H. W. Wilschut,[2] N. A. Orr,[1] J. C. Angélique,[1] C. Borcea,[3] W. N. Catford,[4] N. M. Clarke,[5] P. Descouvemont,[6] J. Díaz,[7] S. Grévy,[1] A. Kugler,[8] V. Kravchuk,[2] M. Labiche,[1,‡] C. Le Brun,[1,§] E. Lienard,[1] H. Löhner,[2] W. Mittig,[9] R. W. Ostendorf,[2] S. Pietri,[1] P. Roussel-Chomaz,[9] M. G. Saint Laurent,[9] H. Savajols,[9] V. Wagner,[8] and N. Yahlali[7]

[1]*Laboratoire de Physique Corpusculaire, IN2P3-CNRS, ISMRA et Université de Caen, F-14050 Caen Cedex, France*
[2]*Kernfysich Versneller Instituut, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands*
[3]*IFIN-HH, P.O. Box MG-6, R0-76900 Bucharest-Magurele, Romania*
[4]*Department of Physics, University of Surrey, Guildford, Surrey, GU2 7XH , United Kingdom*
[5]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*
[6]*Université Libre de Bruxelles, CP 229, B-1050 Bruxelles, Belgium*
[7]*Instituto de Física Corpuscular, E-46100 Burjassot, Spain*
[8]*Nuclear Physics Institute, C7-25068 Řež u Prahy, Czech Republic*
[9]*GANIL, CEA/DSM-CNRS/IN2P3, BP 55027, F-14076 Caen Cedex, France*
(Received 20 February 2001; published 3 July 2001)

Radiative capture of protons is investigated as a probe of clustering in nuclei far from stability. The first such measurement on a halo nucleus is reported here for the reaction ^{6}He(p,γ) at 40 MeV. Capture into ^{7}Li is observed as the strongest channel. In addition, events have been recorded that may be described by quasifree capture on a halo neutron, the α core, and ^{5}He. The possibility of describing such events by capture into the continuum of ^{7}Li is also discussed.

The two main conclusions were, first, the ability to probe the cluster structure of ^{6}He through high-energy photons, and second, the absence of triton-γ coincidences in the exit channel, suggesting that the dominant configuration for the ^{6}He g.s. was α-n-n in which the n-n separation is relatively large. Unfortunately, the beam intensities of other two-neutron halo systems were several orders of magnitude lower, making impracticable the continuation of this program.

4. NEUTRON INTERFEROMETRY

During the same period of time, we decided to extend the breakup program with DEMON at GANIL, started with ^{19}C, with the study of the two-neutron halo systems, ^{6}He, ^{11}Li and ^{14}Be. The experiment focused on the latter, the less well-known of them, but all three were produced at the same time and arrived to the experimental hall in a cocktail beam. At that time, a strong debate in both theory and experiment concerned the relative distance between the two halo neutrons, and we thought that interferometry could contribute to the debate by measuring this distance for the three systems at once.

The interferometry studies I had undertaken with photons exploited the quantum statistical symmetries of identical particles, in the photon case the *attractive* Bose-Einstein statistics that produce a slight enhancement of the $\gamma\gamma$ rate at low relative momentum. In the case of neutrons, the *repulsive* Fermi-Dirac statistics should produce a decrease of the nn rate at low relative momentum, but the attractive s-wave final-state interaction (FSI) at low energies of the two neutrons could overwhelm the Fermi-Dirac repulsion.

Before the experiment, we had to be sure that we would be able to detect neutron pairs at low relative momentum. At tens of MeV, a neutron is mainly detected through elastic scattering on H, and therefore may scatter through several neighboring detectors and mimic a neutron pair, a phenomenon known as cross-talk. We developed Monte-Carlo simulations with Marc Labiche in order to find the geometry of DEMON that would first minimize this effect, and then allow the off-line recognition of cross-talk events, and the results were published in Nuclear Instruments and Methods.

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Nuclear Instruments and Methods in Physics Research A 450 (2000) 109–118

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Neutron cross-talk rejection in a modular array and the detection of halo neutrons

F.M. Marqués*, M. Labiche, N.A. Orr, F. Sarazin[1], J.C. Angélique

Laboratoire de Physique Corpusculaire, IN2P3-CNRS, ISMRA et Université de Caen, F-14050 Caen Cedex, France

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Abstract

Experiments involving neutron-rich radioactive beams often require a high detection efficiency for neutron pairs within a small solid angle. The rejection of cross-talk events under such conditions has been studied for a modular detector array and the optimum array configuration investigated. In parallel, a new algorithm for the rejection of cross-talk events has been developed. By grouping detectors into clusters corresponding to a single-incident neutron, high multiplicity ($M_n \geq 2$) events may be recognized. Results from Monte-Carlo simulations demonstrating the performances of the algorithm are presented. Finally, the application to two-neutron interferometry measurements for halo nuclei is discussed.

The geometry chosen consisted of four walls, as opposed to the single wall of the first GANIL experiment, in which detectors covering neighboring angles were 1-3 meters away from each other. The correlation functions were constructed for the three systems, and an increase of the nn rate at low relative momentum of a factor 5-10 was observed! Indeed, the nn FSI did overwhelm the repulsion between identical fermions, so much that the standard techniques used to extract the correlation function were not enough.

The interference pattern is obtained by constructing an uncorrelated distributions of pairs, through event-mixing techniques, and then by comparing it to the distribution of the experimental ones (the ratio of both is the correlation function). In our case, two effects enhanced the correlation signal: first, the neutrons left the system almost simultaneously, as opposed to standard neutron interferometry which is applied to sources evaporating neutrons over a long time scale; second, the neutrons were spatially delocalized, and thus had a very narrow momentum distribution that lead to low relative momentum values, so that most of the pairs were correlated!

We developed a new iterative technique that was able to remove all correlations, residual ones too, from the data and lead to the fully uncorrelated distribution, and then the correlation function. Using the formalism of Lednicky, that related in a straightforward way the correlation signal to the neutron source size, we obtained the average distance between the two neutrons in the halo of these three systems, in the range 5-7 fm. These results were in good agreement with the prediction of various three-body models, and were published in Physics Letters B.

Physics Letters B 476 (2000) 219–225 PHYSICS LETTERS B

ELSEVIER

Two-neutron interferometry as a probe of the nuclear halo

F.M. Marqués [a], M. Labiche [a], N.A. Orr [a], J.C. Angélique [a], L. Axelsson [b], B. Benoit [c], U.C. Bergmann [d], M.J.G. Borge [e], W.N. Catford [f], S.P.G. Chappell [g], N.M. Clarke [h], G. Costa [i], N. Curtis [f,1], A. D'Arrigo [c], F. de Oliveira Santos [j], E. de Góes Brennand [c], O. Dorvaux [i], M. Freer [h,a], B.R. Fulton [h], G. Giardina [l], C. Gregori [e], S. Grévy [k,2], D. Guillemaud-Mueller [k], F. Hanappe [c], B. Heusch [i], B. Jonson [b], C. Le Brun [a], S. Leenhardt [k], M. Lewitowicz [j], M.J. López [j], K. Markenroth [b], M. Motta [l], A.C. Mueller [k], T. Nilsson [b,3], A. Ninane [a,4], G. Nyman [b], I. Piqueras [e], K. Riisager [d], M.G. Saint Laurent [j], F. Sarazin [j,5], S.M. Singer [h], O. Sorlin [k], L. Stuttgé [i]

[a] *Laboratoire de Physique Corpusculaire, IN2P3-CNRS, ISMRA et Université de Caen, F-14050 Caen cedex, France*
[b] *Fysiska Institutionen, Chalmers Tekniska Högskola, S-412 96 Göteborg, Sweden*
[c] *Université Libre de Bruxelles, CP 226, B-1050 Bruxelles, Belgium*
[d] *Det Fysiske Institut, Aarhus Universitet, DK-8000 Aarhus C, Denmark*
[e] *Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[f] *Department of Physics, University of Surrey, Guildford, Surrey, GU2 5XH, UK*
[g] *Department of Nuclear Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[h] *School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK*
[i] *Institut de Recherche Subatomique, IN2P3-CNRS, Université Louis Pasteur, BP 28, F-67037 Strasbourg cedex, France*
[j] *GANIL, CEA / DSM-CNRS / IN2P3, BP 5027, F-14076 Caen cedex, France*
[k] *Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay cedex, France*
[l] *Dipartimento di Fisica, Università di Messina, Salita Sperone 31, I-98166 Messina, Italy*

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Abstract

The technique of intensity interferometry is proposed as a probe of the spatial configuration of two-neutron haloes. After exploring the sensitivity of interferometry to the n-n configuration, it is demonstrated that the application of the standard method for constructing the correlation function is not valid for halo neutrons. A new iterative method is presented and applied to measurements of the dissociation of ^{6}He, ^{11}Li and ^{14}Be. The correlation functions for these systems have thus been extracted for the first time and the corresponding root-mean-square n-n separations estimated. The results are in agreement with the predictions of available three-body models.

The relatively large average distances measured, in particular that for ^{6}He, was in good agreement with the results of the radiative capture experiment. However, several aspects needed further investigation. The formalism used assumed simultaneous emission of both neutrons, neglecting sequential decays that would add a temporal dimension to the relative distance. And the results obtained were compared to predictions for the g.s. of these nuclei, neglecting the effects of the dissociation reaction on the spatial configuration of the halo neutrons.

5. NEUTRONS ONLY!

A random reading at the LPC library made me come across a paper on *neutral nuclei*, clusters of neutrons that could form a weakly bound or a resonant state. Going through the references I realized that all these searches had lead to negative results due to the extremely weak cross-sections used to create those multineutrons and to the high backgrounds associated to the related detection techniques (well, and maybe because they did not exist). I shared these thoughts with Nigel Orr, who instantly realized that we had much better tools to test their existence!

In the very neutron-rich nuclei we were studying through breakup, these multineutrons should already exist in the low lying states that we were exciting close to the xn threshold, and the breakup cross-sections were several orders of magnitude higher than the ones previously used. The only thing we needed was a clean signature, that we obtained calibrating the light output generated in DEMON by the proton recoil after n-H elastic scattering. This proton recoil energy, obtained from the light output, could be at most that of the incoming neutron, obtained from the time of flight. Anything neutral but heavier than a neutron could lead to a proton recoil beyond that limit.

Before submitting a proposal, we wanted to check the approach with data from the previous campaign. In brief, we were looking for a fragment in the -$4n$ channel in coincidence with an abnormally high proton recoil. The best candidate was ^{14}Be, in which the $4n$ threshold is at only 5 MeV, and to our surprise we found 6 events that could be interpreted as a ^{10}Be fragment in coincidence with a proton recoil 1.5-2.5 higher than expected! After many experimental checks and Monte-Carlo simulations, that excluded the possibility of pile-up of two neutrons in the same DEMON module, we published the results in Physical Review C.

PHYSICAL REVIEW C, VOLUME 65, 044006

Detection of neutron clusters

F. M. Marqués,[1,*] M. Labiche,[1,†] N. A. Orr,[1] J. C. Angélique,[1] L. Axelsson,[2] B. Benoit,[3] U. C. Bergmann,[4] M. J. G. Borge,[5] W. N. Catford,[6] S. P. G. Chappell,[7] N. M. Clarke,[8] G. Costa,[9] N. Curtis,[6,‡] A. D'Arrigo,[3] E. de Góes Brennand,[3] F. de Oliveira Santos,[10] O. Dorvaux,[9] G. Fazio,[11] M. Freer,[8,1] B. R. Fulton,[8,§] G. Giardina,[11] S. Grévy,[12,‖] D. Guillemaud-Mueller,[12] F. Hanappe,[3] B. Heusch,[9] B. Jonson,[2] C. Le Brun,[1,¶] S. Leenhardt,[12] M. Lewitowicz,[10] M. J. López,[10,**] K. Markenroth,[2] A. C. Mueller,[12] T. Nilsson,[2,††] A. Ninane,[1,‡‡] G. Nyman,[1] I. Piqueras,[5] K. Riisager,[4] M. G. Saint Laurent,[10] F. Sarazin,[10,§§] S. M. Singer,[8] O. Sorlin,[12] and L. Stuttgé[9]

[1]*Laboratoire de Physique Corpusculaire, IN2P3-CNRS, ISMRa et Université de Caen, F-14050 Caen Cedex, France*
[2]*Experimentell Fysik, Chalmers Tekniska Högskola, S-412 96 Göteborg, Sweden*
[3]*Université Libre de Bruxelles, CP 226, B-1050 Bruxelles, Belgium*
[4]*Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark*
[5]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[6]*Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[7]*Department of Nuclear Physics, University of Oxford, Keble Road, Oxford OX1 3RH, United Kingdom*
[8]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*
[9]*Institut de Recherche Subatomique, IN2P3-CNRS, Université Louis Pasteur, BP 28, F-67037 Strasbourg Cedex, France*
[10]*GANIL, CEA/DSM-CNRS/IN2P3, BP 55027, F-14076 Caen Cedex, France*
[11]*Dipartimento di Fisica, Università di Messina, Salita Sperone 31, I-98166 Messina, Italy*
[12]*Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France*

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A new approach to the production and detection of bound neutron clusters is presented. The technique is based on the breakup of beams of very neutron-rich nuclei and the subsequent detection of the recoiling proton in a liquid scintillator. The method has been tested in the breakup of intermediate energy (30–50 MeV/nucleon) ^{11}Li, ^{14}Be, and ^{15}B beams. Some six events were observed that exhibit the characteristics of a multineutron cluster liberated in the breakup of ^{14}Be, most probably in the channel ^{10}Be$+^{4}n$. The various backgrounds that may mimic such a signal are discussed in detail.

As expected, the relevance of the results triggered a lot of discussions, experimental proposals and theoretical calculations. Among these proposals were three from us at GANIL, one with a ^{8}He beam from SPIRAL, and two with the same ^{14}Be beam hoping to get higher intensities. All these experiments failed, mainly due to problems around the production of the secondary beam that lead to intensities even lower than the original one. This was the most disappointing period I have met in my career, seeing the tremendous work that so many people were investing during years to have these experiments done and failing to get a result, positive or not, just before the last step. Three times. Note that DEMON was a detector that traveled along different laboratories, so simply getting the detector at GANIL was already a big effort.

The MUST collaboration run an experiment trying a different approach, the α transfer from ^{8}He to a deuteron target, leading to ^{6}Li$+4n$. The measurement of the ^{6}Li momentum did not lead to any narrow peak in the $4n$ missing mass. At the same time, most of the calculations concluded that the changes needed to bind $4n$ were too important to not have a consequence on the properties of other well described light nuclei, though one *ab-initio* calculation did not exclude the possibility of a wide low-lying resonance, that would have been hard to observe in the MUST experiment.

We therefore explored the possibility of a wide $4n$ resonance being at the origin of the 6 events we had observed. We found that, independently of the width, if the resonance was low enough its decay in flight would focus the neutrons forward and increase the probability of several of them being detected in the same module, leading to orders of magnitude comparable to the 6 events we had observed. We submitted these conclusions to Physical Review C, that found that "these were not new results" and denied the publication. We posted it at the arXiv e-print archive.

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CAEN Physique Laboratoire Corpusculaire

On the possible detection of ^{4}n events in the breakup of ^{14}Be

F.M. Marqués[1,a], N.A. Orr[1], H. Al Falou[1], G. Normand[1], N.M. Clarke[2]

[1] *Laboratoire de Physique Corpusculaire, IN2P3-CNRS, ENSICAEN et Université de Caen, F-14050 Caen cedex, France*
[2] *School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*

Abstract: In a recent paper —F.M. Marqués *et al.*, Phys. Rev. C **65**, 044006 (2002)— a new approach to the production and detection of free neutron clusters was proposed and applied to data acquired for the breakup of ^{14}Be. Six events that exhibited characteristics consistent with a bound tetraneutron (^{4}n) were observed in coincidence with ^{10}Be fragments. Here, two issues that were not considered in the original paper are addressed: namely the signal expected from a low-energy ^{4}n resonance, and the detection of a bound ^{4}n through proccesses other than elastic scattering by a proton. Searches complementary to the original study are also briefly noted.

Taking the risk of asking for a ^{14}Be beam at GANIL once more was out of the question. During the last DEMON experiment at GANIL we tried an alternative path, the production of ^{14}Be* in the final state after the -1p reaction on a ^{15}B easier beam. A preliminary analysis of these data lead to no significant signal in the -4n channel, but this could be explained by the fact that proton knock-out from ^{15}B dominantly populates the narrow first 2^+ state of ^{14}Be, that is well below the $4n$ threshold. No other collaboration has reported a result, positive or not, concerning the production of multineutrons. My hope is that our recent implication in the RIKEN experimental program, benefiting from the most intense light neutron-rich beams in the world, will lead to a concluding result in this field.

6. UNCORRELATED DISTRIBUTIONS

When particle pairs are measured, there are three contributions that may arise on top of the uncorrelated distribution one may construct:

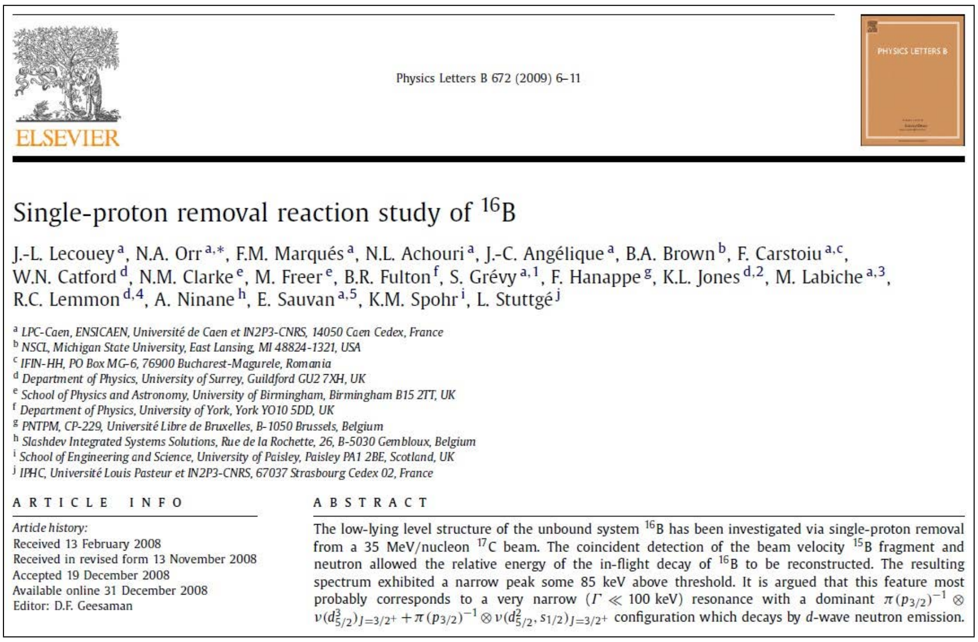
1) quantum statistical symmetries, in the case of identical particles,
2) interactions in the final state or FSI,
3) and decay of intermediate resonances.

In the $\gamma\gamma$ case we saw the first and third (π^0) ones, in the case of nn mainly the second one.

A very important axis of our experimental program has been the search for fragment-n resonances in unbound states just beyond the neutron drip-line, and very quickly we realized that the work we had developed in the nn interferometry studies could be easily extended to the spectroscopy of these unbound states. If fragment-n resonances are formed in these unbound nuclei, the decay of these resonances (or the FSI for virtual s-states) should appear on top of the uncorrelated distribution.

The construction of uncorrelated pairs in this case turned out to follow exactly the same line than that of the nn pairs. For systems in which strongly populated, narrow resonances were formed, the standard event-mixing techniques were unable to fully uncorrelate the pairs, leaving the residual correlations we had first identified in the halo neutron pairs. And exactly the same iterative technique we had developed for the neutrons was able to remove all correlations!

The technique was tested through Monte-Carlo simulations for many different cases, to make sure that it was able to extract resonances but that was not creating them when there were not. The first application was made by Jean-Luc Lecouey on data from the -1p reaction on ^{17}C, that lead to a very narrow resonant state in unbound ^{16}B, only a few tens of keV above threshold, that was published in Physics Letters B.



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PHYSICS LETTERS B

Single-proton removal reaction study of ^{16}B

J.-L. Lecouey [a], N.A. Orr [a,*], F.M. Marqués [a], N.L. Achouri [a], J.-C. Angélique [a], B.A. Brown [b], F. Carstoiu [a,c], W.N. Catford [d], N.M. Clarke [e], M. Freer [e], B.R. Fulton [f], S. Grévy [a,1], F. Hanappe [g], K.L. Jones [d,2], M. Labiche [a,3], R.C. Lemmon [d,4], A. Ninane [h], E. Sauvan [a,5], K.M. Spohr [i], L. Stuttgé [j]

[a] LPC-Caen, ENSICAEN, Université de Caen et IN2P3-CNRS, 14050 Caen Cedex, France
[b] NSCL, Michigan State University, East Lansing, MI 48824-1321, USA
[c] IFIN-HH, PO Box MG-6, 76900 Bucharest-Magurele, Romania
[d] Department of Physics, University of Surrey, Guildford GU2 7XH, UK
[e] School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK
[f] Department of Physics, University of York, York YO10 5DD, UK
[g] PNTPM, CP-229, Université Libre de Bruxelles, B-1050 Brussels, Belgium
[h] Slashdev Integrated Systems Solutions, Rue de la Rochette, 26, B-5030 Gembloux, Belgium
[i] School of Engineering and Science, University of Paisley, Paisley PA1 2BE, Scotland, UK
[j] IPHC, Université Louis Pasteur et IN2P3-CNRS, 67037 Strasbourg Cedex 02, France

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ABSTRACT

The low-lying level structure of the unbound system ^{16}B has been investigated via single-proton removal from a 35 MeV/nucleon ^{17}C beam. The coincident detection of the beam velocity ^{15}B fragment and neutron allowed the relative energy of the in-flight decay of ^{16}B to be reconstructed. The resulting spectrum exhibited a narrow peak some 85 keV above threshold. It is argued that this feature most probably corresponds to a very narrow ($\Gamma \ll 100$ keV) resonance with a dominant $\pi(p_{3/2})^{-1} \otimes \nu(d^3_{5/2})_{J=3/2^+} + \pi(p_{3/2})^{-1} \otimes \nu(d^2_{5/2}, s_{1/2})_{J=3/2^+}$ configuration which decays by d-wave neutron emission.

We extended the technique to three-particle resonances with ^{5}H, where Guillaume Normand demonstrated that a slightly modified iterative algorithm could lead to an uncorrelated t+n+n distribution on top of which appeared a wide peak at about 2 MeV, the g.s. of ^{5}H. A bit later, with Hicham Al Falou we found that for very specific cases the iterative event-mixing technique diverged! Monte-Carlo simulations of those cases demonstrated that, besides the energy correlations, the angular ones had to be taken into account too. An angular weight added during the mixing of events solved the divergence problem, a weight that had been almost constant for all the previous applications of the technique. But for cases in which the resonance decay had very specific kinematics it played an important role and had to be considered.

In the more recent years Anne Leprince and Giacomo Randisi have been extending the use of this technique to very exotic systems, like ^{9}He or ^{12}Li, and studying with increasing detail other systems like ^{10}Li and ^{13}Be. While some groups keep ignoring the uncorrelated contribution to these resonance energy spectra, its importance in the extraction of the resonance parameters is becoming well established in the international community.

7. THREE-BODY INTERACTIONS

We extended the exploratory work on *nn* interferometry we had undertaken on the three known two-neutron haloes, ^{6}He, ^{11}Li and ^{14}Be, searching for three-body correlations. While the data on Pb target indicated that the breakup had been direct, some data on C target lead to bigger *nn* distances, which suggested a contribution of sequential breakup through the formation of fragment-n resonances, the lifetime of which introduced a delay in the emission of the *second* neutron.

We proposed a new representation, the Dalitz plot of the normalized invariant masses of the particle pairs (n-n and fragment-n), that lead to a common boundary for all events independently of their decay energy. In the case of ^{14}Be, this analysis confirmed the absence of ^{13}Be resonances in the breakup on Pb; the neutrons had been thus emitted simultaneously and the distance of about 5 fm measured corresponded well to the *nn* separation in the halo.

However, the breakup on C target exhibited resonances in the ^{12}Be-n channel, responsible for the decrease of the *nn* signal and thus the increase of the distance measured. By fixing the distance to the one obtained on Pb, a *nn* delay below 400 fm/c could be extracted, that would correspond to the average lifetime of all the resonances populated in ^{13}Be. The femtometer had also become a chronometer! These results were published in Physical Review C.

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Three-body correlations in Borromean halo nuclei

F. M. Marqués,[1,*] M. Labiche,[1,†] N. A. Orr,[1] J. C. Angélique,[1] L. Axelsson,[2] B. Benoit,[3] U. C. Bergmann,[4] M. J. G. Borge,[5] W. N. Catford,[6] S. P. G. Chappell,[7] N. M. Clarke,[8] G. Costa,[9] N. Curtis,[6,‡] A. D'Arrigo,[3] E. de Góes Brennand,[3] F. de Oliveira Santos,[10] O. Dorvaux,[9] G. Fazio,[11] M. Freer,[8,1] B. R. Fulton,[8] G. Giardina,[11] S. Grévy,[12,§] D. Guillemaud-Mueller,[12] F. Hanappe,[3] B. Heusch,[9] B. Jonson,[2] C. Le Brun,[1,‖] S. Leenhardt,[12] M. Lewitowicz,[10] M. J. López,[10,¶] K. Markenroth,[2] A. C. Mueller,[12] T. Nilsson,[2,**] A. Ninane,[1,††] G. Nyman,[2] I. Piqueras,[5] K. Riisager,[4] M. G. Saint Laurent,[10] F. Sarazin,[10,‡‡] S. M. Singer,[8] O. Sorlin,[12] and L. Stuttgé[9]

[1]*Laboratoire de Physique Corpusculaire, IN2P3-CNRS, ISMRA et Université de Caen, F-14050 Caen cedex, France*
[2]*Experimentell Fysik, Chalmers Tekniska Högskola, S-412 96 Göteborg, Sweden*
[3]*Université Libre de Bruxelles, CP 226, B-1050 Bruxelles, Belgium*
[4]*Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark*
[5]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[6]*Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[7]*Department of Nuclear Physics, University of Oxford, Keble Road, Oxford OX1 3RH, United Kingdom*
[8]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*
[9]*Institut de Recherche Subatomique, IN2P3-CNRS, Université Louis Pasteur, BP 28, F-67037 Strasbourg cedex, France*
[10]*GANIL, CEA/DSM-CNRS/IN2P3, BP 55027, F-14076 Caen cedex, France*
[11]*Dipartimento di Fisica, Università di Messina, Salita Sperone 31, I-98166 Messina, Italy*
[12]*Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay cedex, France*
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Three-body correlations in the dissociation of two-neutron halo nuclei are explored using a technique based on intensity interferometry and Dalitz plots. This approach provides for the combined treatment of both the n-n and core-n interactions in the exit channel. As an example, the breakup of ^{14}Be into ^{12}Be$+n+n$ by Pb and C targets has been analyzed and the halo n-n separation extracted. Evidence for a finite delay between the emission of the neutrons in the reaction on the C target was observed and is attributed to ^{13}Be resonances populated in sequential breakup.

In the recent years we have been exploring further several aspects of this technique. First, with Guillaume Normand, what is the distance we are measuring. In our first applications we assumed that the *nn* distances were those in the halo of the system g.s., but that neglected the effect of the breakup. A higher statistics run with ^{6}He allowed us to extract the *nn* distance for different gates in the decay energy, or ^{6}He excitation energy spectrum. We found that the gate around the first 2^{+} state lead to a shorter *nn* distance, in agreement with three-body calculations suggesting that this state is relatively compact. Therefore, without gates what we are measuring is the *average of the average* of the *nn* distances in the continuum of the system while it excites and breaks up.

Concerning the time dimension of the decay, the sequentiality we had suggested for ^{14}Be breakup on C has been confirmed by Benoit Laurent with a more appropriate system, ^{8}He. This nucleus has a dominant α-4n structure, but in the three-body breakup into ^{6}He+2n the sequentiality can be easily observed because the subsystem ^{6}He+n has only one, quite narrow state, the g.s. of ^{7}He. And being narrow, it would introduce a significant delay ($\hbar c/\Gamma \sim 1250$ fm/c) that would have a strong effect on the *nn* correlation function.

The analysis of this decay, with the space and time distances between the neutron emission points as free parameters, lead to a *nn* distance during the breakup of ^{8}He of about 7 fm, and to a delay in the emission of the second neutron of about 1400 fm/c, in very good agreement with the lifetime of ^{7}He! These results will be submitted soon for publication.

In our last DEMON experiment we have observed a very promising channel in the -1p reaction on ^{15}B, the excitation of the very narrow 2^{+} state of ^{14}Be. The analysis in progress of the ^{12}Be+2n coincidences in this energy gate will provide valuable information about the configuration and structure of this state.

8. NEXT STEPS

High-energy breakup of very neutron-rich nuclei at GANIL will no longer be feasible, on one hand due of the aging of DEMON, but mainly due to the beam intensities needed. In the last 10 years they have not followed the evolution of other facilities, but have instead almost decreased. The natural extension of our program will begin this year at RIKEN, where the intensities will be several orders of magnitude above our past experience.

We have started a collaboration with our Japanese colleagues at Tokyo and RIKEN around the SAMURAI spectrometer and the NEBULA neutron array, and three experiments have been already accepted for 2012: the search for unbound states in ^{25,26}O and the Coulomb excitation of ^{19}B and ^{22}C (Tokyo), and the study of three-body correlations in the breakup of ^{19}B and ^{22}C plus the structure of the unbound subsystems ^{18}B and ^{21}C (LPC). ^{19}B and ^{22}C are the two heaviest two-neutron halo nuclei, and detailed studies of these systems are out of reach for any other facility in the world.

The multineutron program could be extended at RIKEN too. An experiment will take place this year using the SHARAQ spectrometer. The idea is to use the double charge exchange reaction $^8\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^8\mathrm{Be} + 4n$ and detect the two α particles from ^{8}Be, leaving the $4n$ system almost at rest. We will try to participate depending on our means, but with the experience we will gain during our 2012 runs we should be able to propose our own approaches starting from 2013.

The nn correlation studies will continue at low energies at ISOLDE, where we will measure the correlations between neutrons emitted after the β decay of ^{11}Li. The formalism will be similar to the one used in our breakup experiments, but in this case the states formed in ^{11}Be* after the β decay will emit the neutrons spontaneously, so the information extracted will be free of the reaction mechanism effects we have been neglecting. Depending on the results, a low-energy neutron array should be constructed for these kind of decay experiments at SPIRAL2/DESIR.

These are the steps I can think of now, but many of the steps we have already taken I could not even think about them a few years before, so in the coming years some unexpected things may happen! Or at least that is my hope.

9. THE WORK OF MANY PEOPLE

In a time where our authorities, and our society in general, try hard to individualize the successes, I cannot end this HDR without saying some words about all the people that have been involved in the work I have described in these pages. I may have had some of the ideas, or used the ideas of others, or helped others to finalize their projects... but in the end no one can run an experiment or extract and interpret complex data sets on their own.

My first steps in research were in the Nuclear Physics group at IFIC-Valencia, and were guided by José Lorenzo Ferrero and José Díaz. They taught me the basis of experimental Nuclear Physics and gave me the opportunity to join an international collaboration around the TAPS spectrometer. Working with the other group members, Juan Carlos Pacheco, Facundo Ballester and Ginés Martínez, made things very easy, instructive... and we had a lot of fun! I was happy I had chosen this path.

Then I moved to GANIL, to have a closer link with the TAPS campaign that was coming, under the direction of Yves Schutz. For those who like football, I think that Yves was the *José Mourinho* of Nuclear Physics! He knew how to get the best from each and every member of the group, and I learned a lot about Nuclear Physics but also about self-confidence and motivation, all things that helped me in the continuation of my career. Like Mourinho, he was not always politically correct, but that was motivating too. Having a very original PhD subject was also his fault.

The other group members were key in guiding me through the traps of the PhD. Reint Ostendorf, the student that was working on interferometry before I arrived, that made me enter this subject in a very smooth way. Tomasz Matulewicz, the post-doctorate that shared my office and gave me all the advices I ever needed. Jean Quebert, who I only met a few months but that was ready to answer the most complex questions I could imagine about interferometry. Frédéric Lefèvre, a great help on the acquisition and programming tasks. And Ginés Martínez again, that came to GANIL as much as he could and that avoided any blocking point in my analyses with his advice, always friendly and critique at the same time. Without Reint, Tomasz and specially Ginés, my PhD would have been very poor despite all the means I had around me.

Working in a international collaboration was very instructive, and some of the members had a strong impact in the training of the students. I remember specially Romain Holzmann, from GSI, and our colleagues from KVI-Groningen, Herbert Löhner and Hans Wilschut, that would come back and help me again a few years later for the radiative capture experiment.

In September 1994, after failing the CNRS audition and the grant requests I had filled, I decided to quit Nuclear Physics, and research in general. José Lorenzo Ferrero, José Díaz and Yves Schutz made their best to make me change my mind, and finally found a few months of CNRS visitor at LPC-Caen. Christian Lebrun gave me the possibility to join the Exotic Nuclei group, Nigel Orr and Jean-Claude Angélique, and after those few months he kept making efforts to find some support that would allow me to stay there at least until the CNRS auditions of 1995. I think that if I finally became a researcher was in part due to Christian.

I was under heavy pressure, because I had to change field, analyze an experiment and prepare the CNRS audition all in a few months! But working with Nigel Orr made all things possible. I did not lose a single minute because he has the most complete knowledge of Nuclear Physics in general (and his field in particular) I have ever seen, and knows the things you have to read or do and the things you have not to. Another one guilty, maybe one of the most, of my career in research is Nigel. I also benefited from the knowledge and availability of Karsten Riisager, that made my transition to these new physics much easier.

During my PhD I did the work I was given, as best as I could, but once I got my position at CNRS I had “freedom to research”. Right from the start I tried to look for original things that could be done, and being guided by Nigel was, as we say in Spanish, like practicing flying trapeze with a safety net! Any bizarre, weird or fool suggestion received instantaneously the verdict: interesting / already done / nonsense. It is extremely easy to work this way, and if you do not think so try flying trapeze without safety net and you will understand...

Another ingredient that helped me tremendously was the long list of very good students we have been supervising all these years. Some of them were selected, but most were not, so I consider myself very lucky of the good interaction we had, all the work we did together, and I am very happy and proud of the fact that most of them have found their own way in research, far from us! Since 1996 I was able to share many hours of work with Marc Labiche, Frédéric Sarazin, Emmanuel Sauvan, Jean-Luc Lecouey, Guillaume Normand, Hicham Al Falou, Benoit Laurent, Anne Leprince and Giacomo Randisi. Six have now a permanent position in research, one is very close to, and the two latest ones have postdoctoral grants that I hope will lead them soon to something better. I tried to play the role for them that Yves Schutz played for me, and I know that some of them are already supervising students, so the chain goes on.

With Marc I shared our first steps in exotic nuclei, and worked together a lot on simulations and the analysis programs. Emmanuel was hopefully there when the radiative capture experiment was approved, it was a project too big for me and sometimes people thought that he was not a student but one of the spokespersons. Jean-Luc and Guillaume were there at the *tetraneutron period*, and we worked a lot to get the second, third, fourth... experiment ready to see the result almost on-line. But there was nothing to see, on- or off-line, I was upset for me but upset for them too, and I am happy that after several years away they are back in Caen. Benoit spent almost half of his time looking for tetraneutrons without success, and managed to write a very good PhD in the time left! He has been the first one we have worked with as a “researcher colleague”. Hicham, Anne and Giacomo focused on unbound systems, and despite having as a starting point the work that had been done before, they all found their way to provide original contributions to the field. Hicham was never afraid to ask questions and discuss, a true researcher! I remember being very proud when I read Anne’s PhD reports, the best ones I had ever read! At the writing of these pages Giacomo has not yet finished his PhD, but I am sure he will make a great defense. He will leave a hole in the group and in the laboratory.

Being in a small laboratory has forced us to create collaborations in order to undertake the complex experimental program we have been running. The KVI group of the TAPS collaboration, and specially Hans Wilschut, played a key role in the “photons from the halo” project, first measuring the contribution of the core at KVI, identifying the dominant capture mechanism, and finally helping us in the setup of the Château de Cristal at GANIL. Our Belgian colleagues of the DEMON collaboration, Francis Hanappe and Alain Ninane, and Louise Stuttgé from Strasbourg saved our life many times setting up the 100 DEMON modules almost on their own. And our British colleagues of the CHARISSA collaboration, Nobby Clarke, Martin Freer and Wilton Catford, allowed us to detect all kinds of charged particles in coincidence with the neutrons. I learned a lot from them all.

The laboratory may be small, but you can always find someone for anything you need! I will not give the names because we are about 80 people and I would need to give almost 80 names, but from the day I arrived at LPC everyone made their best to make me feel at home. The secretary and computer services for the everyday issues, the mechanics and electronics services for the preparation, setting up and running of the experiments. All our collaborators are jealous of how easy it is to prepare an experiment with the LPC teams. I would like to have a special thought for two colleagues that passed away, Jean-Marc Gautier and Gilles Iltis, that were strongly involved in the experiments we run at GANIL, we all miss them. The fact that groups are open and everybody can happen to work together puts LPC apart from all other laboratories, the overall great atmosphere that fills the corridors being the consequence, or the cause, and I think all the directors that have guided the LPC during these years share the responsibility. Those of you who have not experienced other laboratories cannot appreciate how lucky you are, and how hard life is outside!

A few years after my arrival the “Exotic Group” was exotic, an Australian and a Spaniard, but not so much a group. With the arrival of Lynda Achouri, and then Franck Delaunay, and then Julien Gibelin, the group has consolidated and we feel strong enough to undertake the coming programs at ISOLDE, RIKEN, SPIRAL2... I think we complement each other very well.

The fact that this section has been the longest one of the HDR should tell you how small my contribution to the results I have shown has been, as well as how many people have contributed to these 21 years of research. Without many of them I would not be writing this document today. I did not like the idea of writing the HDR, a degree that does not exist in Spain, but at least it will have served to give me the opportunity to thank them all. I tried to highlight only the names I remember the most (I am getting old), but this list should have been even longer.

10. TEACHING DUTIES

I had begun teaching during my PhD at the University of Valencia, but when I came to France right after that I was advised to try the CNRS because "ton Français n'est pas assez bon pour enseigner" (and by the way, because "une thèse de Valence n'est pas assez prestigieuse pour le CEA"). I was glad to *choose* the CNRS!

But a few years later my French became not-too-bad enough to try teaching again, and I did at some Doctoral Schools here and there (see CV). From 2008, I have been teaching regularly at the Master 2 in Caen, a complement of 6h about "Light neutron-rich nuclei", and at the Master 2 NPAC at Orsay, an introduction of 15h to "The atomic nucleus".

As an example of this part of my career, I have included the written lecture I gave at the Joliot-Curie School in 2002, which summarizes within a simple approach several aspects of the experimental programs I have described.

Haloes, molecules and multineutrons†

F. Miguel MARQUÉS MORENO

Laboratoire de Physique Corpusculaire,
IN2P3-CNRS, ENSICAEN et Université de Caen, F-14050 Caen cedex, France

Abstract: Away from the equilibrium between protons and neutrons within stable nuclei, many exotic nuclei exist. Most of the known nuclear properties evolve smoothly with exoticism, but some extreme proton-neutron combinations have revealed during the last decade completely new concepts. They will be illustrated through three examples: the extended and dilute halo formed by very weakly bound neutrons, the molecular-like neutron orbitals found in nuclei exhibiting α clustering, and the recently revived debate on the possible existence of neutral nuclei. The different experimental results will be reviewed, and we will see how several properties of these new phenomena can be well understood within relatively simple theoretical approaches.

† Lecture presented at "École Joliot-Curie de Physique Nucléaire", Maubuisson (France), Sep. 8 14 2002.

Contents

In all these years, and mostly in the last three (NPAC has about 30-40 students per year), I have met many students and some have already started their way in research. I consider this, together with all the students that have done their PhD with us, a result to be placed at the same level or higher than all the papers I have listed.

CURRICULUM VITÆ

– Nom, prénom : *MARQUÉS MORENO, Francisco Miguel.*
– Naissance : *le 22 août 1968 à Tormos (Espagne).*
– Nationalité : *espagnole.*
– État civil : *marié (trois enfants).*
– Profession : *chercheur (CR1) du CNRS.*
– Adresse : *Laboratoire de Physique Corpusculaire,*
6 Bd. du Maréchal Juin, F-14050 Caen cedex (France),
Tél : +[33/0] 23145 2967 / 2549 (fax),
E-mail : marques@lpccaen.in2p3.fr.
– Langues : *Anglais, Français, Espagnol (lu, parlé, écrit) et Catalan (lu, parlé).*

EXPERIENCE SCIENTIFIQUE

1996–2012 : LPC-Caen. Chargé de Recherche du CNRS dans le groupe *"Noyaux Exotiques"*. Étude de corrélations et recherche de nouveaux phénomènes dans les noyaux légers très riches en neutrons. Exploration de nouvelles techniques, telles que l'interférométrie neutronique, la capture radiative de protons, l'émission de neutrons après décroissance β, ou la detection d'agregats de neutrons.

1994/95 : LPC-Caen. Post-doctorat de la CEE sur l'étude du halo du ^{19}C avec DéMoN.

1991–94 : GANIL-Caen/IFIC-Valence. Travail sur les *"Corrélations Bose-Einstein entre photons durs produits dans les collisions d'ions lourds"* sous la direction de Yves SCHUTZ et José Lorenzo FERRERO CALABUIG.

1990/91 : IFIC-Valence. Travail sur l' *"Étude et développement du détecteur CPV pour des expéreinces au GANIL avec le multidétecteur de photons TAPS"* sous la direction de José Lorenzo FERRERO CALABUIG.

FORMATION

1994 : Thèse de Doctorat en Espagnol et Français (GANIL T9405) à l'Université de Valence.
Mention : distinction spéciale "Premio Extraordinario".

1992 : "Tesina" (Thèse troisième cycle) à l'Université de Valence.
Mention : Très Honorable.

1990 : "Licenciado" (Maîtrise et DEA) en Physique Nucléaire à l'Université de Valence.
Mention : distinction spéciale "Premio Extraordinario".

1985 : Baccalauréat Scientifique au Lycée IES Cid Campeador, Valence (Espagne).
Mention : Très Bien.

ENSEIGNEMENT

– Cours :
  – Mécanique, 2$^{\text{ème}}$ année de Sciences Chimiques, Université de Valence (Espagne), 1993/94 ;
  – Algèbre, 1$^{\text{ère}}$ année de Sciences Physiques, Université de Valence (Espagne), 1993/94 ;
  – *Des noyaux trop riches en neutrons*, École Doctorale CSIC-Madrid (Espagne), 6h du 3–5 mars 2003 ;
  – *Systèmes à petit nombre de nucléons*, École Doctorale SIMEM-Caen/CESCS-Orsay,
    12h à l'Université de Caen (France), 15–19 mai 2006 ;
    12h à l'IPN Orsay (France), 25–29 mai 2009 ;

  - *Noyaux l 'egers riches en neutrons*, Master de Physique-Recherche, Université de Caen et ENSICAEN (France),
    6h en 2008/2009 ;
    6h en 2009/2010 ;
    6h en 2010/2011 ;
    6h en 2011/2012 ;
  - *Le noyau de l'atome*, Master 2 NPAC, Université de Paris VI-VII-XI (France),
    15h en 2009/2010 ;
    15h en 2010/2011 ;
    15h en 2011/2012 ;
  - *De Paris à Hiroshima*, Ecole d'été JANUS GANIL-LPC 2010,
    3h en 2010.
- Co-direction de Thèse :
  - Emmanuel SAUVAN, Université de Caen (1997–2000) ;
  - Guillaume NORMAND, Université de Caen (2001–2004) ;
  - Hicham AL FALOU, Université de Caen (2003–2007) ;
  - Benoit LAURENT, Université de Caen (2004–2007) ;
  - Anne LEPRINCE, Université de Caen (2006–2009) ;
  - Giacomo RANDISI, Université de Caen (2008–2011).
- Encadrement du travail de Thèse :
  - Emmanuel LIEGARD, Université de Caen (1994–97) ;
  - Marc LABICHE, Université de Caen (1996–99) ;
  - Jean-Luc LECOUEY, Université de Caen (1999-2002) ;
  - Virginie BOUCHAT, Université de Bruxelles (2002–2005).
- Direction de stage de DEA :
  - Fréderic SARAZIN, Université de Caen (1996) ;
  - Jean-Luc LECOUEY, Université de Caen (1999) ;
  - Guillaume NORMAND, Université de Caen (2001) ;
  - Hicham AL FALOU, Université de Caen (2003) ;
  - Benoit LAURENT, Université de Caen (2004) ;
  - Anne LEPRINCE, Université de Caen (2006).
- Direction de stage de Maîtrise :
  - Alan VIGNER et Clément HUOT-MARCHAND, Université de Caen (1997) ;
  - Guillaume NORMAND et Nicolas BLARD, Université de Caen (1999).
- Encadrement de TIPE :
  - Abdoul Saheb HUSSAINI, Lycée Jean Perrin, Lyon (2002) ;
  - Vincent ROUGET, Lycée Saint-Louis, Paris (2002).

PUBLICATIONS AVEC COMITE DE LECTURE

1) R.S. Mayer ... F.M. Marqués ... Z. Sujkowski,
"Investigation of pion absorption in heavy-ion induced subthreshold π^0 production",
Physical Review Letters 70 (1993) 904.

2) A. Schubert ... F.M. Marqués ... J. Québert,
"Evidence for stopping in heavy-ion collision from study of hard-photon source velocities",
Physical Review Letters 72 (1993) 1608.

3) F.M. Marqués ... Z. Sujkowski,
"Hard photon intensity interferometry in heavy ion reactions",
Physical Review Letters 73 (1994) 34.

4) A. Schubert ... F.M. Marqués ... J. Québert,
"Investigation of polar and azimuthal distributions of subthreshold pions at intermediate energies",
Physiscs Letters B 328 (1994) 10.

5) G. Martínez ... F.M. Marqués ... H.W. Wilschut,
"Impact parameter dependence of hard photon production in intermediate energy heavy-ion collisions",
Physiscs Letters B 334 (1994) 23.

6) P.E. Mueller ... F.M. Marqués ... A. Marín,
"Heavy ion Coulomb excitation and gamma decay studies of the one and two phonon giant dipole resonances in ^{208}Pb and ^{209}Bi",
Nuclear Physics A 569 (1994) 123c.

7) F.M. Marqués ... Y. Schutz,
"Identification of photons and particles in the segmented electromagnetic calorimeter TAPS",
Nuclear Instruments and Methods A365 (1995) 392.

8) G. Martínez, F.M. Marqués ... H.W. Wilschut,
"Bremsstrahlung photons as a probe of hot nuclei",
Physics Letters B 349 (1995) 23.

9) F.M. Marqués ... Gy. Wolf,
"Density oscillations in systems of colliding heavy ions observed via hard-photon interferometry measurements",
Physics Letters B 349 (1995) 30.

10) J.H.G. van Pol ... F.M. Marqués ... H.W. Wilschut,
"Hard photons as a probe to study dissipation mechanisms",
Nuclear Physics A 583 (1995) 373c.

11) R. Holzmann ... F.M. Marqués ... J. Québert,
"Pion reabsorption in heavy-ion collisions interpreted in terms of the Δ capture process",
Physics Letters B 366 (1996) 63.

12) J.H.G. van Pol ... F.M. Marqués ... A. Kugler,
"Importance of one- and two-body dissipation at intermediate energies studied by hard photons",
Physical Review Letters 76 (1996) 1425.

13) F.M. Marqués ... D.D. Wagner,
"Neutrons from the breakup of ^{19}C",
Physics Letters B 381 (1996) 407.

14) K.K. Gudima ... F.M. Marqués ... A. Marín,
"Subthreshold pion dynamics as a source for hard photons beyond proton-neutron bremsstrahlung in heavy-ion collisions",
Physical Review Letters 76 (1996) 2412.

15) T. Matulewicz ... F.M. Marqués ... Y. Schutz,
"Identification of hydrogen isotopes with the BaF_2 electromagnetic calorimeter TAPS",
Nuclear Instruments and Methods A 378 (1996) 179.

16) F.M. Marqués ... Y. Schutz,
"Comment on : Analysis of hard two-photon correlations measured in heavy-ion reactions at intermediate energies",
Physical Review C 54 (1996) 2783.

17) F.M. Marqués ... Y. Schutz,
"Two-slit interference of bremsstrahlung photons from heavy-ion reactions",
Physics Letters B 394 (1997) 37.

18) F.M. Marqués ... Y. Schutz,
"Two-photon correlations : from quantum statistics to heavy-ion collision dynamics",
Physics Reports 284 (1997) 91.

19) Y. Schutz, G. Martínez, F.M. Marqués ... Gy. Wolf,
"Hard photons and neutral pions as probes of hot and dense nuclear matter",
Nuclear Physics A 622 (1997) 404.

20) A. Marín ... F.M. Marqués ... Gy. Wolf,
"Exclusive π^0*- and* η*-meson production in* $^{40}Ar+^{\mathrm{nat}}Ca$ *at 800A MeV"*,
Physics Letters B 409 (1997) 77.

21) F.M. Marqués,
"Comment on : Measurement of the space-time extent of the hard-photon emitting source in heavy-ion collisions at 100 MeV/nucleon",
Physical Review C 57 (1998) 2763.

22) A. Marín ... F.M. Marqués ... V. Wagner,
"Detection of charged pions and protons in the segmented electromagnetic calorimeter TAPS",
Nuclear Instruments and Methods A 417 (1998) 137.

23) M. Freer ... F.M. Marqués ... D.L. Watson,
"Exotic molecular states in ^{12}Be*"*,
Physical Review Letters 82 (1999) 1383.

24) M. Labiche, F.M. Marqués, O. Sorlin, N. Vinh Mau,
"Structure of ^{13}Be *and* ^{14}Be*"*,
Physical Review C 60 (1999) 027303.

25) U.C. Bergmann ... F.M. Marqués ... K. Wilhelmsen Rolander,
"New information on β*-delayed neutron emission from* $^{12,14}Be$*"*,
Nuclear Physics A 658 (1999) 129.

26) F.M. Marqués ... L. Stuttgé,
"Two-neutron interferometry as a probe of the nuclear halo",
Physics Letters B 476 (2000) 219.

27) F.M. Marqués ... J.C. Angélique,
"Neutron cross-talk rejection in a modular array and the detection of halo neutrons",
Nuclear Instruments and Methods A 450 (2000) 109.

28) E. Sauvan ... F.M. Marqués ... J.S. Winfield,
"One-neutron removal reactions on neutron-rich psd-shell nuclei",
Physics Letters B 491 (2000) 1.

29) M. Hoefman ... F.M. Marqués ... E. Wulf,
"Coherent bremsstrahlung in the $\alpha+p$ *system at 50 MeV/nucleon"*,
Physical Review Letters 85 (2000) 1404.

30) A. Buţă ... F.M. Marqués ... M. Sandu,
"TONNERRE : an array for delayed-neutron decay spectroscopy",
Nuclear Instruments and Methods A 455 (2000) 412.

31) M. Labiche, N.A. Orr, F.M. Marqués ... L. Stuttgé,
"Halo structure of ^{14}Be*"*,
Physical Review Letters 86 (2001) 600.

32) M. Freer ... F.M. Marqués ... D.L. Watson,
"Helium breakup states in ^{10}Be *and* ^{12}Be*"*,
Physical Review C 63 (2001) 034301.

33) P.J. Leask ... F.M. Marqués ... L. Stuttgé,
"Search for molecular states in ^{16}C*"*,
Journal of Physics G 27 (2001) B9.

34) E. Sauvan, F.M. Marqués ... N. Yahlali,
"Radiative proton capture on ^{6}He*"*,
Physical Review Letters 87 (2001) 042501.

35) F.M. Marqués ... L. Stuttgé,
"Three-body correlations in Borromean halo nuclei",
Physical Review C 64 (2001) 061301.

36) F.M. Marqués ... L. Stuttgé,
"Detection of neutron clusters",
Physical Review C 65 (2002) 044006.

37) N.A. Orr, F.M. Marqués,
"Clustering and correlations at the neutron dripline",
Comptes Rendus Physique 4 (2003) 451.

38) S. Ahmed ... F.M. Marqués ... V.A. Ziman,
"Breakup reaction studies of ^{10}Be *and* $^{10,11}B$ *using a* ^{10}Be *beam"*,
Physical Review C 69 (2004) 024303.

39) E. Sauvan ... F.M. Marqués ... M. Shawcross,
"One-neutron removal reactions on light neutron-rich nuclei",
Physical Review C 69 (2004) 44603.

40) N.I. Ashwood ... F.M. Marqués ... V.A. Ziman,
"Measurements of the breakup and neutron removal cross-sections for ^{16}C*"*,
Physical Review C 70 (2004) 064607.

41) N.I. Ashwood ... F.M. Marqués ... V.A. Ziman,
"Neutron removal and cluster breakup of ^{14}B *and* ^{14}Be*"*,
Physical Review C 70 (2004) 024608.

42) N.I. Ashwood ... F.M. Marqués ... V.A. Ziman,
"Helium clustering in neutron-rich Be isotopes",
Physics Letters B 580 (2004) 129.

43) N.I. Ashwood ... F.M. Marqués ... V.A. Ziman,
"High-energy two-neutron removal from ^{10}Be*"*,
Physical Review C 72 (2005) 024314.

44) F.M. Marqués ... N.M. Clarke,
"On the events consistent with a tetraneutron",
[nucl-ex/0504009].

45) F.M. Marqués,
"The four neutron system",
Few Body Systems 44 (2008) 269.

46) M. Madurga ... F.M. Marqués ... K. Wilhelmsen,
"Study of β-delayed 3-body and 5-body breakup channels observed in the decay of ^{11}Li",
Nuclear Physics A 810 (2008) 1-12.

47) J.L. Lecouey, N.A. Orr, F.M. Marqués ... L. Stuttgé,
"Single-proton removal reaction study of ^{16}B",
Physics Letters B 672 (2009) 6.

48) F.M. Marqués,
"Light nuclei in the continuum",
Few Body Systems, 45 (2009) 137.

49) Y. Fujita ... F.M. Marqués ... J.C. Thomas,
"Nuclear weak response from the combined study of β-decay and charge exchange reactions",
International Journal of Modern Physics E, Vol. 18, No. 10 (2009) 2134.

50) F.M. Marqués ...,
"Multi-particle correlations in the dissociation of two-neutron halo nuclei",
En préparation.

51) B. Laurent, F.M. Marqués ...,
"Space and time in the sequential breakup of ^{8}He",
En préparation.

52) F.M. Marqués ...,
"Event mixing in experiments with neutron-rich beams",
En préparation.

AUTRES PUBLICATIONS

1) F.M. Marqués,
"Noyaux à halo Borroméens et autres structures exotiques",
Rapport d'activité IN2P3 1998–2000.

2) F.M. Marqués,
"Des neutrons en zone interdite",
Images de la physique 2003.

CONFERENCES

1) *"The CP veto detector at GANIL : preliminary tests"*,
I TAPS Workshop, Schiermonnikoog (Pays Bas), septembre 1990, Ed. W. Kühn et H. Löhner [**GSI-91-21 (1991) 188**].

2) *"Two-photon interferometry : the experiment"*,
II TAPS Workshop, Guardamar (Espagne), 31 mai au 5 juin 1993, Ed. J. Díaz, G. Martínez and Y. Schutz [**World Scientific (1994) 98**].

3) *"Noyaux à halo : du ^{11}Li au ^{19}C"*,
II Colloque GANIL, Le Pradet (France), 2 juin 1995.

4) *"Study of nuclear halo along the neutron drip-line"*,
10th General Conference of the European Physical Society, Seville (Espagne), 9–13 septembre 1996.

5) *"Two-photon interference in micro- and macro-systems"*,
XXV Mazurian Lakes School of Physics, Piaski (Pologne), 27 août au 6 septembre 1997 [**Acta Physica Polonica B 29 (1998) 211**].

6) *"Probing the halo with intensity interferometry"*,
Experimental Nuclear Physics in Europe (ENPE 99), Seville (Espagne), 21–26 juin 1999, Ed. B. Rubio, M. Lozano and W. Gelletly [**AIP CP495 (1999) 15**].

7) *"Mapping the space-time dissociation of two-neutron haloes"*,
XVIIth Conference on Few-Body Problems in Physics, Évora (Portugal), 11–16 septembre 2000, Ed. A. Stadler *et al.* [**Nuclear Physics A689 (2001) 555c**].

8) *"Probing few-body correlations in two-neutron halo nuclei"*,
I Colloque GDR "Noyaux Exotiques", Caen (France), 14–15 décembre 2000.

9) *"Probing correlations in many-body haloes"*,
International Conference on Nuclear Physics at Border Lines, Lipari (Italie), 21–24 mai 2001, Ed. G. Fazio *et al.* [**World Scientific (2002) 183**].

10) *"Correlations in neutron-rich nuclei"*,
Workshop on Physics with SPIRAL II, Paris (France), 28–29 mai 2001.

11) *"Probing few-body correlations in light, neutron-rich nuclei"*,
International Workshop on Dynamics and Structure of Critically Stable Quantum Few-Body Systems, Les Houches (France), 8–13 octobre 2001 [**Few-Body Systems 31 (2002) 145**].

12) *"Des noyaux dans le noyau"*,
Société Française de Physique, journées de la division Physique Nucléaire, Caen (France), 5–6 mars 2002.

13) *"États moléculaires, halos : expérience et théorie"*,
École Internationale Joliot-Curie, Maubuisson (France), 8–14 septembre 2002.

14) *"Des noyaux trop riches en neutrons"*,
Conférences sur la Radioactivité, Conseil Régional de Basse-Normandie, Caen (France), 29 janvier 2003.

15) *"Núcleos demasiado ricos en neutrones"*,
École de Doctorat, Madrid (Espagne), 3–5 mars 2003.

16) *"The search for neutral nuclei"*,
Tours Symposium on Nuclear Physics V, Tours (France), 26–29 août 2003.

17) *"Nuclei 100% neutron rich"*,
Colloque Noyaux Exotiques, Orsay (France), 17–19 septembre 2003.

18) *"Multineutron clusters (experimental perspective)"*,
ENAM'04, the Fourth International Conference on Exotic Nuclei and Atomic Masses, Pine Mountain (Georgia, États Unis), 12–16 septembre 2004.

19) *"Research on neutron clusters"*,
Exotic Nuclei and Nuclear/Particle Astrophysics, Carpathian Summer School of Physics 2005, Mamaia-Constanta (Roumanie), 13–24 juin 2005, Ed. S. Stoica *et al.* [**World Scientific (2006) p5**].

20) *"Systèmes à petit nombre de nucléons"*,
École Doctorale SIMEM-Caen/CESCS-Orsay, Université de Caen, 15–19 mai 2006.

21) *"Correlations in many-neutron systems"*,
IX International Conference on Nucleus Nucleus Collisions 2006, Rio de Janeiro (Brésil), 28–1 août/septembre 2006.

22) *"Probing correlations in many-neutron systems"*,
The Physics of Halo Nuclei, ECT*, Trento (Italie), 30 octobre au 3 novembre 2006.

23) *"Neutron clusters and correlations"*,
Clusters '07, Stratford-upon-Avon (Royaume Uni), 3-7 septembre 2007.

24) *"The four neutron system"*,
The 20th European Conference on Few-Body Problems in Physics, Pisa (Italie), 10-14 septembre 2007.

25) *"Light Nuclei in the Continuum"*,
5th Workshop on Critical Stability of Few-Body Quantum Systems, Erice (Italie), 13-17 octobre 2008.

26) *"Three-body correlations in the breakup of halo nuclei"*,
Continuum and correlations in light nuclei, ECT*, Trento (Italie), 6-10 juin 2011.

SEMINAIRES

1) *"Distributions angulaires de neutrons issus de la cassure du ^{19}C"*,
CRN, Strasbourg (France), 30 mars 1995 ;
LPC-GANIL, Caen (France), 7 avril 1995 ;
IPN, Orsay (France), 11 avril 1995.

2) *"Núcleos con halo : del ^{11}Li al ^{19}C"*,
IFIC, Valence (Espagne), 18 mai 1995.

3) *"Nuclear haloes : candidates and experimental techniques"*,
IFIC, Valence (Espagne), 18 juin 1998 ;
Universidad Autónoma, Madrid (Espagne), 24 juin 1998.

4) *"Two-neutron interferometry from nuclear haloes"*,
LPC-GANIL, Caen (France), 10 juillet 1998 ;
University of Surrey, Guildford (Royaume Uni), 15 septembre 1998 ;
University of Birmingham, Birmingham (Royaume Uni), 16 septembre 1998.

5) *"Les noyaux à halo"*,
Conférence sur Centenaire de la Radioactivité, Lycée Charles de Gaulle, Caen (France), 9 octobre 1998.

6) *"Intensity interferometry : a new probe of the nuclear halo"*,
CSIC, Madrid (Espagne), 17 décembre 1998 ;
IFIC, Valence (Espagne), 21 décembre 1998.

7) *"Probing extreme states of nuclear matter with intensity interferometry"*,
KVI, Groningen (Pays Bas), 26 janvier 1999.

8) *"Une introduction à l'interférométrie"*,
LPC, Caen (France), 25 mars 1999.

9) *"Allo ? ... Il y a des interférences dans le halo !"*,
GANIL-LPC, Caen (France), 7 mai 1999.

10) *"Corrélations à trois corps dans les noyaux à halo"*,
CENBG, Bordeaux (France), 17 novembre 2000 ;
SUBATECH, Nantes (France), 23 novembre 2000.

11) *"Triple correlations in the dissociation of Borromean haloes"*,
GDR "Halos, peaux et drip lines", GANIL, Caen (France), 30 octobre 2000.

12) *"Correlaciones a tres cuerpos en el núcleo"*,
IFIC, Valence (Espagne), 19 décembre 2000 ;
Universidad de Sevilla, Seville (Espagne), 21 décembre 2000 ;
CSIC, Madrid (Espagne), 22 décembre 2000.

13) *"Les noyaux Borroméens sondés par réaction et décroissance"*,
IRES, Strasbourg (France), 22 mars 2001 ;
DAPNIA-SPhN, Saclay (France), 23 mars 2001.

14) *"À la recherche des noyaux neutres"*,
LPC, Caen (France), 29 mars 2001 ;
GANIL, Caen (France), 17 avril 2001.

15) *"En búsqueda de núcleos neutros"*,
IFIC, Valence (Espagne), 6 juin 2001.

16) *"Clusters et halos dans le noyau"*,
Conseil Scientifique du GANIL, Caen (France), 18 juin 2001.

17) *"Correlations in few-neutron systems"*,
University of Warsaw, Varsovie (Pologne), 9 novembre 2001.

18) *"Les neutrons ont-ils besoin des protons ?"*,
GANIL, Caen (France), 11 janvier 2002 ;
IPN, Orsay (France), 4 mars 2002 ;
ISN, Grenoble (France), 28 mars 2002.

19) *"The detection of neutron clusters"*,
GDR "Halos, peaux et drip lines", GANIL, Caen (France), 7 février 2002.

20) *"Un noyau á neutrons ?"*,
CEA-DAM, Bruyères-le-Châtel (France), 13 mai 2002.

21) *"Un autre regard sur le noyau atomique"*,
Union des Physiciens, Lycée Malherbe, Caen (France), 19 juin 2002 ;
Secteurs Techniques et Administratif du LPC, Caen (France), 21 novembre 2002.

22) *"On the existence of neutral nuclei"*,
SUBATECH, Nantes (France), 26 septembre 2002.

23) *"Des systèmes à grand nombre de neutrons"*,
PCC College de France, Paris (France), 31 octobre 2002.

24) *"Teneur en neutrons = 100%"*,
CSNSM, Orsay (France), 20 novembre 2003.

25) *"Search for neutral nuclei : a review of the LPC experimental programme"*,
Conseil Scientifique du GANIL, Caen (France), 16 décembre 2003.

26) *"Filling up nuclei with neutrons"*,
Colorado School of Mines, Golden (États Unis), 9 septembre 2004.

27) *"Des noyaux trop riches en neutrons"*,
GANIL, Caen (France), 16 mai 2005.

28) *"Neutral nuclei from breakup"*,
Conseil Scientifique du GANIL, Caen (France), 9 juin 2005.

29) *"Un chercheur en Physique Nucléaire"*,
École Primaire, Cresserons (France), 3 février 2007.

30) *"À la recherche du noyau"*,
Séminaire du LPC, Cabourg (France), 20 septembre 2007.

31) *"De Paris à Hiroshima"*,
LPC, Caen (France), 19 et 25 novembre 2009 ;
SUBATECH, Nantes (France), 4 et 5 février 2010 ;
IFIC, Valence (Espagne), 17 et 18 mai 2010 ;
Universidad de Huelva, Huelva (Espagne), 24 mars 2011.

32) *"De los rayos-X a la fisión del átomo : la carrera hacia la bomba"*,
IES Cid Campeador, Valence (Espagne), 19 décembre 2011 ;
CSIC, Madrid (Espagne), 20 décembre 2011.

AUTRES ACTIVITES

- Coordinateur de coopérations internationales :
  - IN2P3-CICYT (Espagne), "Structure de noyaux légers riches en neutrons produits au GANIL", avec Berta RUBIO de l'IFIC-Valence (1997–2003) ;
  - IN2P3-FOM (Pays Bas), "Study of two-neutron halo nuclei with proton-induced bremsstrahlung", avec Hans WILSCHUT du KVI-Groningen (1999–2001) ;
  - IN2P3-MEC (Espagne), "Étude de noyaux exotiques par réaction et décroissance", avec Berta RUBIO de l'IFIC-Valence (2004–2012).
- Coresponsable du projet ANR "Neutromania" (2005–2007).
- Organisateur des séminaires GANIL-LPC (1999–2003).
- Responsable du Rapport d'Activité du LPC (1996/97).
- Membre du Conseil de Laboratoire du LPC (2005–2009).
- Participation à l'opération "Sciences au Village", Fête de la Science (2005–2006).
- Participation à l'opération "Village des Sciences", Fête de la Science (2008–2011).
- Porte-parole des expériences :
  - E302 GANIL, rayonnement de freinage dans le système p-^{6}He (1997/98) ;
  - E378 GANIL, corrélations multiples dans les isotopes lourds d'Helium (2000) ;
  - E415 GANIL, recherche de multineutrons et corrélations dans la cassure du ^{14}Be (2002).
  - E483 GANIL, recherche de multineutrons et corrélations dans la cassure du ^{14}Be (2005).
- Séjours :
  - CRN-Strasbourg, initiation aux calculs de potentiel optique (1990) ;
  - KVI (Pays Bas), construction du détecteur CPV pour TAPS (1991) ;
  - Louvain-la-Neuve (Belgique), système d'acquisition de DéMoN (1996) ;
  - IFIC (Espagne), calculs de structure de systèmes borroméens (1997–2001).
- Participation à des expériences dans d'autres accélérateurs :
  - CERN (Suisse), coll. TAPS-CERES, décroissance Dalitz de mesons (1993) ;

– GSI (Allemagne), coll. TAPS, production de mesons sous le seuil (1994) ;
– CERN-ISOLDE (Suisse), décroissance β-n du ^{14}Be (1998) ;
– CERN-ISOLDE (Suisse), décroissance β-n-particules du ^{9,11}Li (2003) ;
– RIKEN (Japon), mesure d'états excités non-liés de l'^{24}O (2009).

Caen, le 24 janvier 2012